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Tribological evaluation of surface modified H13 tool steel in warm forming of Ti–6Al–4V titanium alloy sheet

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KEYWORDS

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Tools;
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Wear

Abstract The H13 hot-working tool steel is widely used as die material in the warm forming of Ti–6Al–4V titanium alloy sheet. However, under the heating condition, severe friction and lubricating conditions between the H13 tools and Ti–6Al–4V titanium alloy sheet would cause difficulty in guaranteeing forming quality. Surface modification may be used to control the level of friction force, reduce the friction wear and extend the service life of dies. In this paper, four surface modification methods (chromium plating, TiAlN coating, surface polishing and nitriding treatment) were applied to the H13 surfaces. Taking the coefficient of friction (CoF) and the wear degree as evaluation indicators, the high-temperature tribological behavior of the surface modified H13 steel was experimentally investigated under different tribological conditions. The results of this study indicate that the tribological properties of the TiAlN coating under dry friction condition are better than the others for a wide range of temperature (from room temperature to 500 °C), while there is little difference of tribological properties between different surface modifications under graphite lubricated condition, and the variation law of CoF with temperature under graphite lubricated is opposite to that under the dry friction.

1. Introduction

The Ti–6Al–4V titanium alloy has been extensively used in aerospace, automobile, ship, chemical and energy industries, and the share of Ti–6Al–4V products in the titanium alloy production accounts for more than 50%.[1] Heating method is a feasible way to reduce the deformation resistance of Ti–6Al–4V and improve its formability, and it has been the primary method to form the titanium alloy components.[2] However, forming temperature above the recrystallization

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temperature of the Ti–6Al–4V titanium alloy will lead to great changes in mechanical property and surface quality of Ti–6Al–4V titanium alloy, such as phase transition and surface oxidation, which are not conform to the ordinary demands in some stamping forming of some semi-finished Ti–6Al–4V sheet. Therefore, the warm forming method may be a suitable way to improve the formability and keep the mechanical property of Ti–6Al–4V sheet. Under the condition of warm forming, the service life of dies and forming quality will be more easily influenced by the extremely friction conditions than that in cold forming. Thus it is very important to choose appropriate tool material to improve friction conditions between
Ti–6Al–4V and forming tools in warm forming.

H13 is one of the most universal hot-working tool steels with good high-temperature strength and ductility, and it is suitable for die manufacturing used in Ti–6Al–4V titanium alloy sheet warm forming.[3] However, the H13 tool steel shows a high coefficient of friction (CoF) and suffers poor resistances to sliding wear. Therefore there is a growing interest in using surface engineering techniques to improve the tribological properties of the hot work tool steel.[4] Nitriding, polishing, chromium electro-plating and hard coatings deposited by PVD/CVD method are all applicable surface modification techniques.

Nitriding is a common practice already applied in the H13 tool steels,[5] which has proved to be effective in improving the life of H13 steel tools by two to three times.[6] And this may attribute to the improved tensile strength and wear resistance after nitriding treatment.[3] Another way to improve the friction condition between the contacting surfaces of forming tools is surface polishing. Related researches showed that the polishing has a great effect on the tribological behavior of contacting surfaces,[7,8] and this is because the surface roughness and the relative hardness of the contacting surfaces are the key factors determining the contact friction conditions.[9] While chromium plating has also been applied in H13 due to its low CoF, low wettability and low adhesion,[10] and it shows satisfactory long-term wear resistance better than that of the uncoated and CrN coated H13 steel.[11] In the last couple of years, hard coatings deposited by PVD/CVD method have been successfully used for high wear resistance and long service life of dies.[12–18] However, the researches mainly focus on the wear resistance[12–14] and machinability[15–17] while the combined tribological properties are not mentioned. What's more, the hard coatings are just widely used for cutting tool applications, and the applications in H13 steel used as sheet forming tools are rare.[19]

In conclusion, Ti–6Al–4V titanium alloy sheet parts are widely applied to advanced aircraft and spacecraft, but the precision forming and service life of forming tool are still a problem to be solved. And until now there are few researches aimed at finding a proper surface modification solution suitable for the Ti–6Al–4V titanium alloy sheet warm forming tool. In this paper, the tribological properties of four surface modified H13 steels (the chromium plating, TiAlN coating, surface polishing and nitriding treatment) used in warm forming of Ti–6Al–4V titanium alloy sheet are compared via the high temperature friction and wear experiments under various lubricating conditions and at different temperatures. Then, a proper surface modification can be determined and precise friction evaluation can be conducted.

2. Experiments

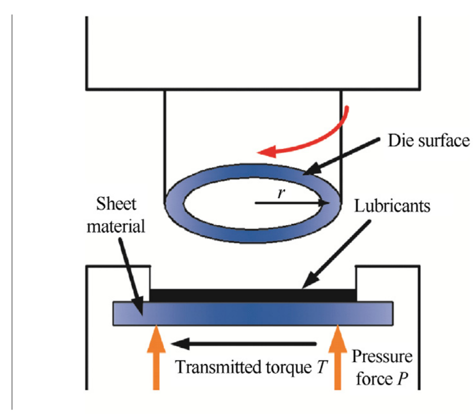
2.1. Friction test procedure

The high-temperature twist compression test (TCT) was used for the determination of the tribological characteristics and the CoF under various tribological conditions. Since several variables such as sheet material, tool material, temperature, pressure force, types of lubricant and large rotate speed can be varied under dynamic contact conditions while remaining a constant contact area in the test, the high-temperature TCT is proper to reproduce the dynamic contact conditions of warm forming of Ti–6Al–4V titanium alloy sheet.[20] Fig. 1 shows the device of high-temperature TCT and the corresponding specimens. In the test, a rotating annular tool is pressed against a fixed sheet metal specimen, while the pressure and torque are measured. According to the Coulomb law, the CoF can be calculated according to Eq. (1):

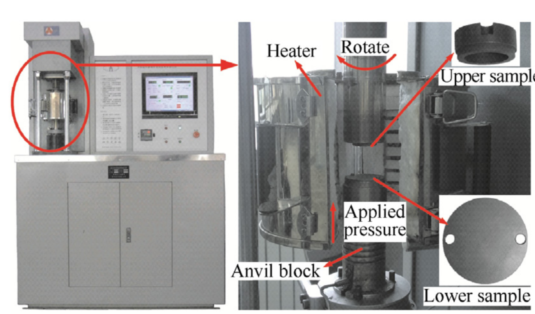
$$\mu = \frac{F}{P} = \frac{T}{PrA} \tag{1}$$

where μ is the CoF, F is the friction force between the tool and the sheet metal specimen, P is the normal contact pressure exerted by the tool on the sheet metal specimen, T is the friction twist torque transmitted from the tool to the sheet metal specimen, r is the mean radius of the tool, and A is the cross-sectional area of the annular tool.

Table 1 shows the experimental parameters. In the practical warm forming process of Ti–6Al–4V titanium alloy sheet, the yield strength reduces evidently and the plasticity improves much at 500 °C, so 500 °C may be a proper warm forming tem-



(a) Schematic of test



(b) Setup of test

Fig. 1 High-temperature TCT friction test.

Table 1 Parameters used in TCT friction test.

Test parameter	Value	Uncertainty
Temperature (°C)	20/300/500	±2
Rotating speed (r/min)	6	±1
Pressure (N)	500	±1%
Friction time (s)	120	

perature to keep the material properties to the maximum extent and successfully deform as well. Therefore, the friction test temperature was assigned as 500 °C. A normal force of 500 N was applied to the contacting specimens, which was selected with a consideration of the forces acting on die bearing during warm forming of Ti–6Al–4V titanium alloy sheet, too. Moreover, another two groups of temperature (room temperature and 300 °C) were added to the tests to explore the influence of temperature on the tribological properties of different surface modifications.

As shown in Fig. 2, the CoF was calculated by averaging the history CoF data which varies with time. The wear was determined through qualitative analysis supported by the LEICA-DMI3000M optical microscope.

2.2. Surface modifications

As shown in Fig. 1(b), the material of upper sample is H13 tool steels, and lower sample is Ti–6Al–4V titanium alloy sheet with thickness of 1 mm. Table 2 shows the composition of H13. In order to explore the tribological properties of surface modification applied in the warm forming tools, several test surface modified H13 specimens were prepared. There are chromium plating, TiAlN coating, surface polishing and nitriding treatment.

Hard chromium coating was obtained by electrodepositing in a chromic acid bath in which the temperature was 38–50 °C and the current density was 25 A/dm^2 for 20 min. TiAlN coating was generated by commercial PVD method of pulse multi arc ion plating. The deposition experiment was conducted at 550 °C for 60 min; the current of titanium target and aluminum target were 80 and 60 A respectively; the N2 partial pressure was 1.0 Pa and the negative bias of substrate was 50 V. The surface polishing specimens were prepared by grinding and polishing using 2000 grains waterproof abrasive paper, which gave average surface roughness values R_a of 0.02 μm. Nitriding treated specimens were gained by plasma nitriding at temperature of 500 °C for 8 h. The different surface modified specimens are shown in Figs. 3 and 4 shows their micrographs.

Table 3 shows the mechanical properties of different surface modifications as well as their surface characteristics. The microhardness was tested by HXP-1000TM/LCD microhardness tester, and roughness is measured through TR200 surface roughometer. It is found that the hardness was improved a lot after the surface modification, and the hardness of TiAlN coating is almost 10 times of the untreated specimen.

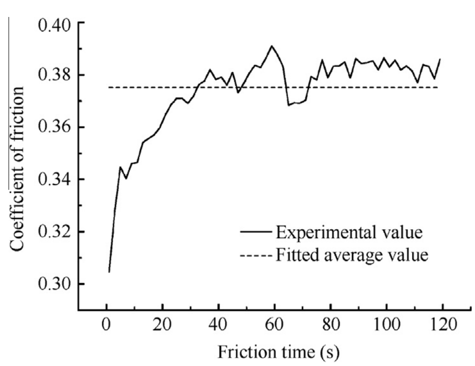


Fig. 2 Data processing method.

3. Results and discussion

3.1. Friction and wear characteristics

Fig. 5 shows the CoFs of different surface modification methods at 500 °C and dry friction condition. The value of the bar chart in Fig. 5(b) is based on the average value of the curve in the Fig. 5(a). It is observed that the CoF of the TiAlN coated H13 steel shows the smallest value, followed by polishing, chromium plating, and nitriding treatment. Compared with the untreated specimen, the CoFs of all the surface modification methods decrease.

Fig. 5(a) shows the history CoFs which varies with time and it can be observed from it that the CoF curve of TiAlN coating

Table 2 Composition of H13 die steel.

Elements	C	Si	Mn	Cr	Mo	V	S	P	Fe
wt.%	0.32–0.45	0.8–1.2	0.2–0.5	4.75–5.50	1.10–1.75	0.8–1.2	⩽0.03	⩽0.03	Bal.

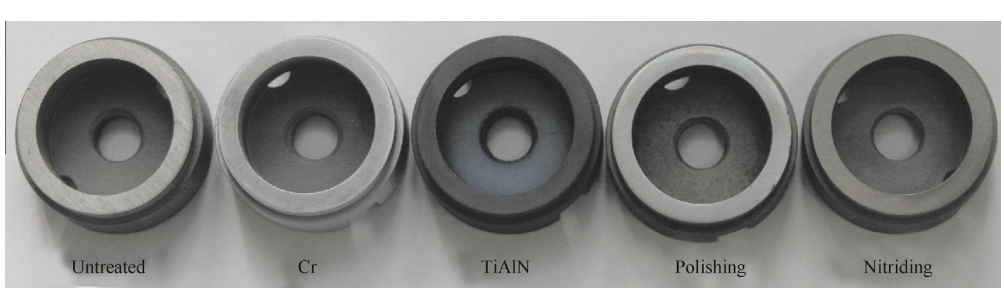


Fig. 3 Different surface modification methods of forming tool specimens.

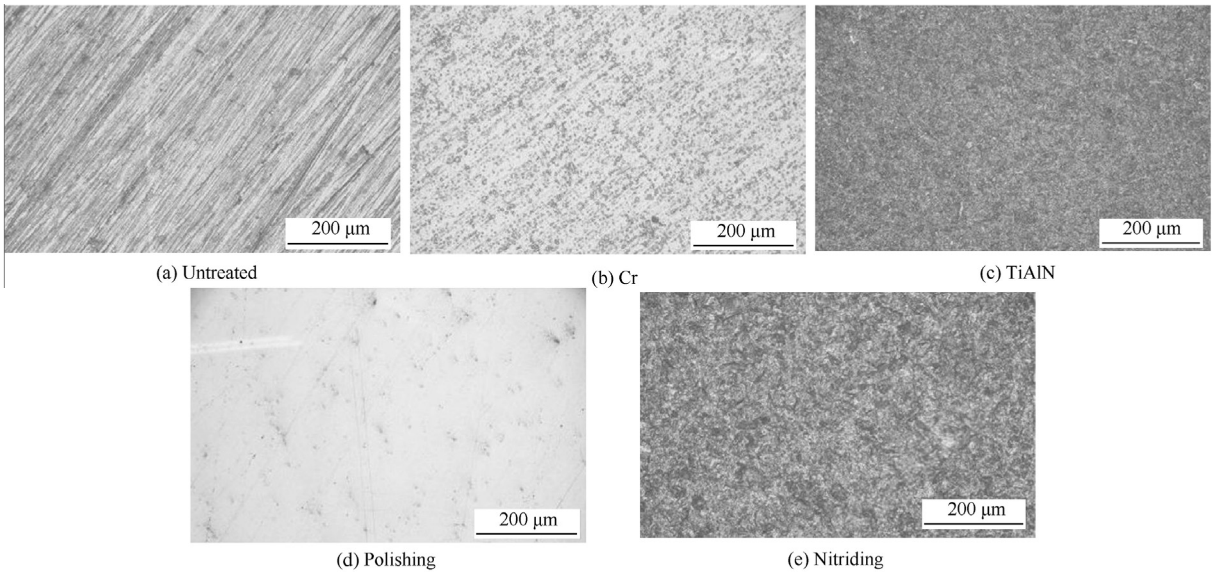


Fig. 4 Optical micrographs of different surface modification methods of forming tool specimens before friction test.

Table 3 Mechanical properties and surface characteristics of surface modification methods.

Specimen	Thickness (μm)	Hardness (HV)	R_a (μm)
Untreated		235	0.426
Cr	10	485	0.411
TiAlN	3	2343	0.418
Polishing		221	0.016
Nitriding	100	622	0.407

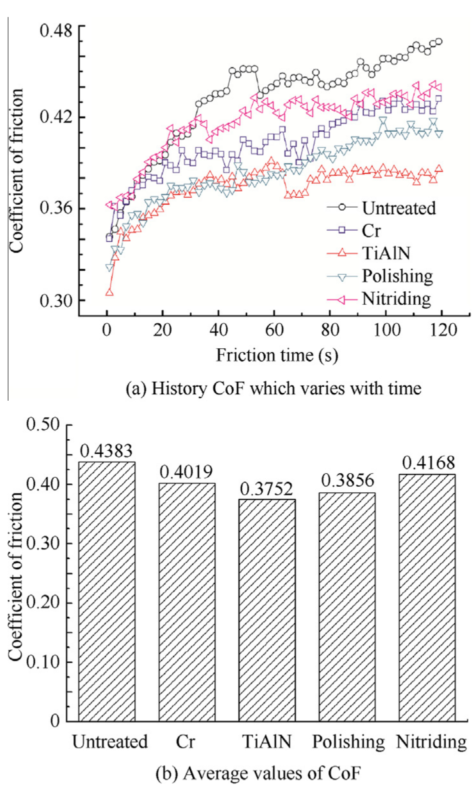


Fig. 5 CoFs of different surface modification methods under conditions of 500 °C and dry friction.

is steadier than other ones, and others' CoFs show an increasing trend with increasing friction time. It may attribute to the high hardness and good lubricating property of TiAlN coating. During the later period of the friction test, the abrasive particle of TiAlN can absorb much more load because of its high hardness. Moreover, surface oxidation has already appeared at 500 °C in some parts of TiAlN. Normally, TiAlN is oxidized to form mixture of TiO_2 and Al_2O_3. The shear strength of TiO_2 is low, which can be acted as the lubricant. While the Al_2O_3 owns higher strength, which has the protective effect of anti wear. Therefore, the TiAlN can absorb load and work as lubricant to a certain degree, and the negative effect of material delaminating and abrasive accumulation can be neutralize, which keeps the CoF at a stable value relatively.

Figs. 6 and 7 show the surface conditions and micrographs of different surface modification methods of warm forming tools specimens after test. It is observed that severe galling and abrasion appear in a large range of areas for the untreated forming tools specimen. Both the chromium plating and nitriding treatment reduce the abrasion to a certain degree; however, the galling and abrasion can still be obviously observed. The polishing specimen keeps a relatively smooth surface, and only a fine ring galling area is visible. TiAlN coating shows excellent anti-galling and anti-friction characteristics compared with others. For TiAlN coating, there is no apparent wear trace in the surface of warm forming tools specimen; moreover, only little coating delaminating is observed from the optical micrographs.

Fig. 8 shows the surface conditions of various Ti–6Al–4V specimens. Under the condition of 500 °C, the titanium alloy sheets oxidize to different degrees. The adhesion and galling phenomena are observed on the surfaces of untreated, chromium coated and nitriding treated specimens (shown in the circles). While slight abrasion appeared on the surfaces of polishing and TiAlN coated specimens.

The results above attribute to the highest hardness of TiAlN coating. Because hard surface can effectively bear the load, TiAlN coating helps reduce the degree of deformation

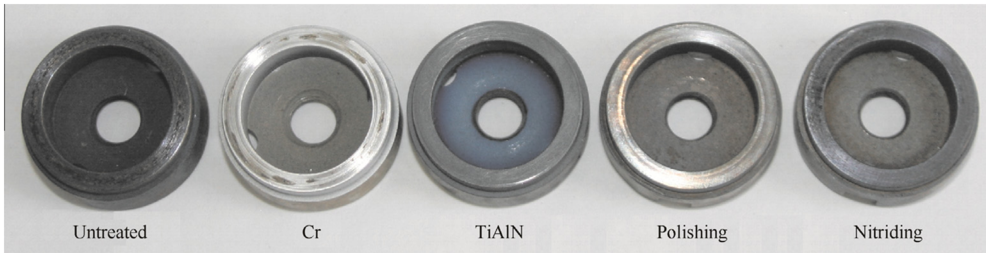


Fig. 6 Surface conditions with different surface modification methods of warm forming tool specimens after test under conditions of 500 °C and dry friction.

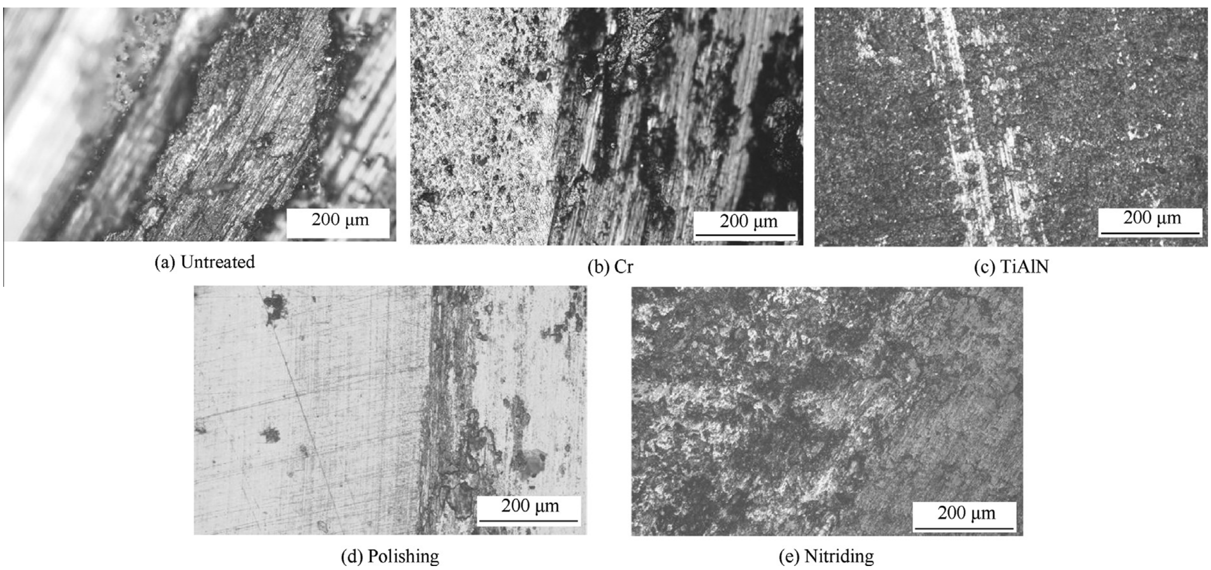


Fig. 7 Optical micrographs of different surface modification methods of forming tool specimens after friction test under conditions of 500 °C and dry friction.

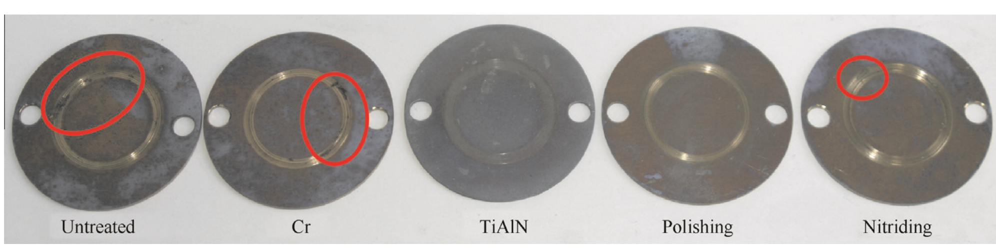


Fig. 8 Surface condition of Ti–6Al–4V specimen after test under conditions of 500 °C and dry friction.

and leads to smaller contact area between forming tool and Ti–6Al–4V titanium alloy sheet specimen. It helps reduce the value of CoF and wear degree, and thus the aim to improve the tribological properties is able to be realized.

Figs. 9–11 show the CoFs and surface conditions of different surface modified H13 forming tool specimens and Ti–6Al–4V titanium alloy sheet specimens under the conditions of 500 °C and graphite lubricated. Under the lubricated condition, the friction condition improves sharply, and the CoFs keep at a low value for all the specimens. The excellent TiAlN coating under dry friction no longer shows the distinguished properties under the condition of graphite lubricated. It can be observed that there are still residual lubricants on the surfaces of the warm forming tools and Ti–6Al–4V titanium alloy sheet specimens from Figs. 10 and 11. Under the condition of graphite lubricated, the surfaces of specimens get well protected, and the surface effects weaken, which leads to minimal difference between different surface modification methods.

Experimental results show that under the conditions of 500 °C and dry friction, the TiAlN coating significantly improves the friction condition. The CoF reduces and the wear degree between the surfaces of the forming tools and Ti–6Al–4V titanium alloy sheet specimens is slight. However, under condition of 500 °C and graphite lubricated, the improvement effect of all the surface modification methods is limited.

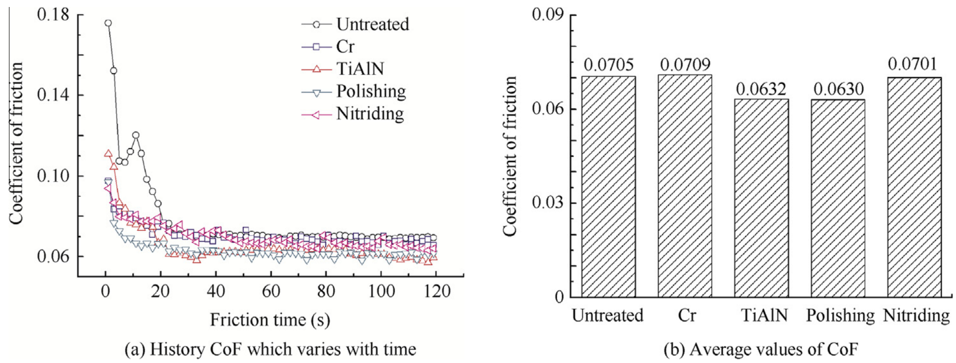


Fig. 9 CoFs of different surface modification methods under conditions of 500 °C and graphite lubricated.

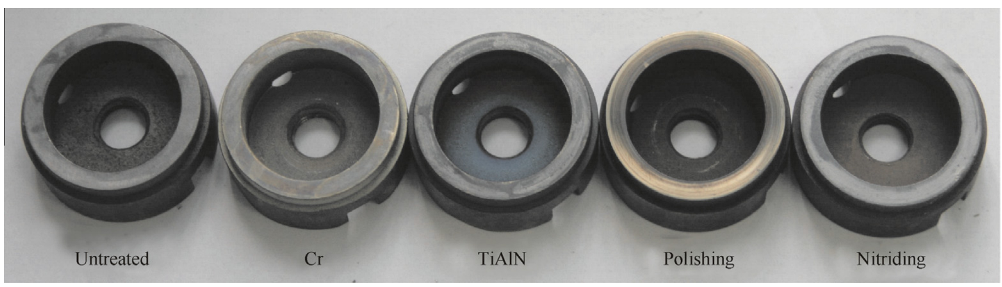


Fig. 10 Surface conditions with different surface modification methods of forming tool specimens after test under conditions of 500 °C and graphite lubricated.

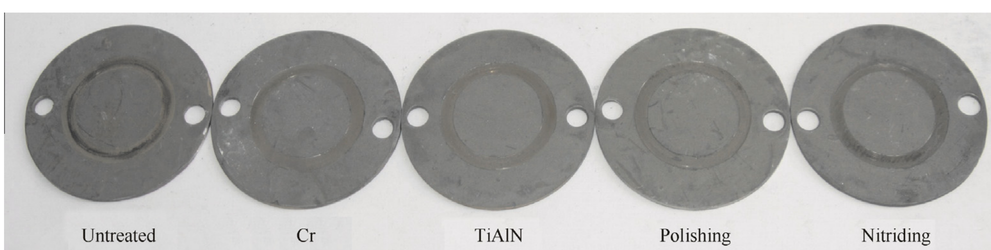


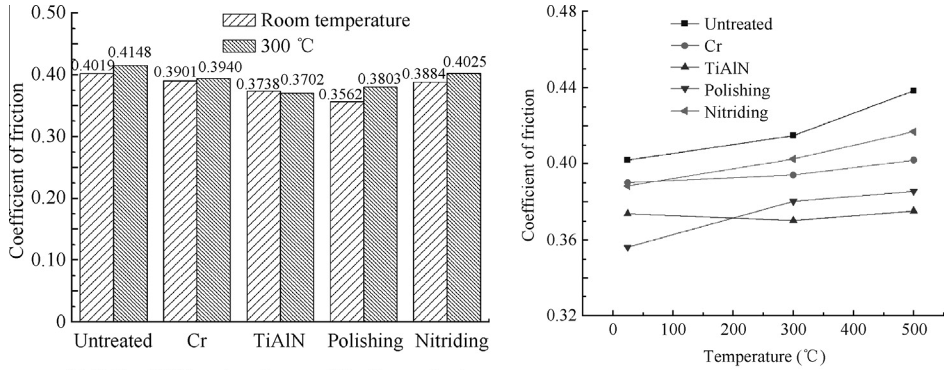
Fig. 11 Surface condition of Ti–6Al–4V specimen after test under the conditions of 500 °C and graphite lubricated.

3.2. Influence of temperature on tribological properties

The friction experiments at different temperatures were also conducted to explore the influence of temperature on the frictional behavior of all the surface modification methods. Fig. 12 shows how the temperature affects the CoF of different surface modifications under the condition of dry friction.

As shown in Fig. 12, under the conditions of room temperature, 300 °C and 500 °C, the CoF of the untreated specimen is always the biggest, which indicates that the method of surface modification is effective to improve the friction condition. At room temperature, the smallest CoF is obtained through surface polishing, followed by TiAlN coating, nitriding treatment, and chromium plating. It is because real surface topography of polishing specimens (R_a = 0.02 μm) is much better than the others' (R_a = 0.4 μm). The excellent surface topography would reduce the number and height of the peaks of asperities in contact, so the CoF decreases due to improved contacting condition. With the increase of temperature, the CoFs of the untreated specimen, nitriding treatment, surface polishing and chromium plating all significantly increase under the condition of dry friction. While from room temperature to 500 °C, the temperature has little influence on the CoF of the TiAlN coating; the CoF of the TiAlN coating almost maintains a relatively stable value. It can be concluded that the TiAlN coating owns a good temperature stability of CoF, viz., the fluctuation of CoF varying with temperature is small, and the TiAlN coating can be used in a wide range of temperature.

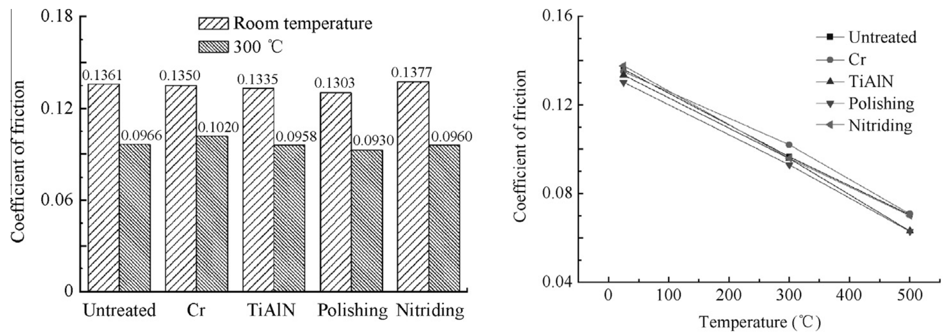
The results of friction experiments under the conditions of different temperatures and graphite lubricated are shown in Fig. 13. It can be observed that there is little difference between the surface modification and untreated specimens, and the CoFs of all the specimens decrease with the increment of temperature. The variation law of CoF with temperature under the condition of graphite lubricated is opposite to that under the dry friction. It is considered that there almost does not exist the accumulation of abrasive particle due to slight



(a) CoFs of different surface modification methods under conditions of room temperature and 300 ℃

(b) CoF vs temperature curves for different surface modification methods

Fig. 12 Influence of temperature on CoF of surface modification under condition of dry friction.



(a) CoFs of different surface modification methods under condition of room temperature and 300 ℃

(b) CoF vs temperature curves for different surface modification methods

Fig. 13 Influence of temperature on the CoF of surface modification under the condition of graphite lubricated.

abrasion under the condition of graphite lubricated, the tool material tends to soften during the increasing process of temperature, and the lubricating effect of graphite becomes better at high temperature. These reasons help to make the friction condition improve and the surfaces of specimens slip well. In a word, under the condition of graphite lubricated, the surface modification has little effect on temperature stability of CoF; and the CoF decreases with the increase of temperature.

In conclusion, friction behavior is very complicated at elevated temperature. Both the lubricating condition and tool materials greatly affect the tribological properties. Under dry friction condition, the CoFs of different surface modification methods vary greatly. It attributes to the different cutting effects of peaks of the asperities for different materials. Normally, increasing temperature would increase the thickness of oxidation film, and then the cutting effects of the asperities would become severe. Therefore, the CoFs increase with the increase of temperature under the dry friction. While the oxide of TiAlN coating helps to improve the friction and wear condition. It is no wonder that TiAlN coating shows excellent temperature stability of CoF and wear resistant for a wide range of temperature among the four surface modification methods. However, under graphite lubricated condition, perfect lubricating condition makes the differences of cutting effects of the asperities between different surface modification specimens become smaller. So the CoFs of all the specimens are almost the same.

4. Conclusions

In the present study, four different surface modification methods, viz., chromium plating, TiAlN coating, surface polishing and nitriding treatment, have been applied to surfaces of H13 tool steel. Their tribological properties have been evaluated in sliding contact against Ti–6Al–4V titanium alloy sheets. The ollowing conclusions are obtained.

(1) The friction behavior under dry friction is different from that under graphite lubricated condition. First, under dry friction condition, the different surface modification methods affect the tribological properties a lot. While under graphite lubricated condition, the CoFs and wear conditions of different surface modification methods are similar. Second, under dry friction, the CoF has an increasing trend with the increase of temperature, while under graphite lubricated condition the CoF decreases with the increasing of temperature.
(2) Among all the surface modified H13 steel specimens, the TiAlN coated H13 specimen shows the best tribological properties. Under the conditions of dry friction and 500 °C, the CoF of TiAlN coating reduces the most compared with other specimens and the wear degree of H13 and Ti–6Al–4V specimens is the slightest. And the temperature stability of CoF of TiAlN coating is also

the best under dry friction. The TiAlN coating can be used as the surface modification method of H13 tool steels in Ti–6Al–4V titanium alloy sheet warm forming.

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References

1. Park NK, Yeom JT, Na YS. Characterization of deformation stability in hot forging of conventional Ti–6Al–4V using processing. *J Mater Process Technol* 2002;**130–131**:540–5.
2. Xu QH. Numerical simulation study on forming process of large TC4 alloy cylindrical component [dissertation]. Nanjing: Nanjing University of Aeronautics and Astronautics; 2012 [Chinese].
3. Karamig MB. An investigation of the properties and wear behavior of plasma-nitrided hot-working steel (H13). *Wear* 1991;**150**(1):331–42.
4. Liao F. PN + PECVD duplex treatment on the surface of H13 steel: preparation and mechanical properties [dissertation]. Changsha: South China University of Technology; 2012 [Chinese].
5. Akhtar SS, Arif AFM, Yilbas BS. Evaluation of gas nitriding process with in-process variation of nitriding potential for AISI H13 tool steel. *Int J Adv Manuf Technol* 2010;**47**(5–8):687–98.
6. Devi MU, Chakraborty TK, Mohanty ON. Wear behavior of plasma nitrided tool steels. *Surf Coat Technol* 1999;**116–119**:212–21.
7. Podgornik B, Hogmark S. Surface modification to improve friction and galling properties of forming tools. *J Mater Process Technol* 2006;**174**(1):334–41.
8. Sheu S, Hector LG, Richmond O. Tool surface topographies for controlling friction and wear in metal-forming processes. *ASME J Tribol* 1998;**120**(3):517–27.
9. Leu DK. Modeling of surface roughness effect on dry contact friction in metal forming. *Int J Adv Manuf Technol* 2011;**57**(5–8):575–84.
10. Fedrizzi L, Rossi S, Bellei F, Deflorian F. Wear-corrosion mechanism of hard chromium coatings. *Wear* 2002;**253**(11–12):1173–81.
11. Chiu LH, Yang CF, Hsieh WC, Cheng AS. Effect of contact pressure on wear resistance of AISI H13 tool steels with chromium nitride and hard chromium coatings. *Surf Coat Technol* 2002;**154**(2–3):282–8.
12. Raou M, Mirdamadi S, Mahboubi F, Ahangarani S, Mahdipoor H, Elmkhah H. Effect of active screen plasma nitriding pretreatment on wear behavior of TiN coating deposited by PACVD technique. *Appl Surf Sci* 2012;**258**(20):7820–5.
13. Birol Y, Yuksel B. Performance of gas nitrided and AlTiN coated AISI H13 hot work tool steel in aluminium extrusion. *Surf Coat Technol* 2012;**207**:461–6.
14. Miao Q, Cui CE, Pan JD, Duan LH, Liu YP. Tribological behavior of magnesium alloy AZ91 coated with TiN/CrN by arc-glow plasma depositing. *Chin J Aeronaut* 2006;**19**(3):266–70.
15. Ng EG. The effect of workpiece hardness and cutting speed on the machinability of AISI H13 hot work die steel when using PCBN tooling. *J Manuf Sci E-T ASME* 2002;**24**(3):588–94.
16. Fallböhmer P, Rodriguez PA, Özel T, Altan T. High-speed machining of cast iron and alloy steels for die and mold manufacturing. *J Mater Process Technol* 2000;**98**(1):104–15.
17. Su HH, Liu P, Fu YC, Xu JH. Tool life and surface integrity in high-speed milling of titanium alloy TA15 with PCD/PCBN tools. *Chin J Aeronaut* 2012;**25**(5):784–90.
18. Zhou QG, Bai XD, Chen XW, Peng DQ, Ling YH, Wang DR. Corrosion resistance of duplex and gradient CrNx coated H13 steel. *Appl Surf Sci* 2003;**211**(1–4):293–9.
19. Hou YK, Zhang WG, Yu ZQ, Li SH. Selection of tool materials and surface treatments for improved galling performance in sheet metal forming. *Int J Adv Manuf Technol* 2009;**43**(9–10):1010–7.
20. Yang H, Li H, Zhan M. Friction role in bending behaviors of thin-walled tube in rotary-draw-bending under small bending radii. *J Mater Process Technol* 2010;**210**(5):2273–84.

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